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Thermodynamics of cosmological matter creation

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ABSTRACT **A type of cosmological history that includes large-scale entropy production is proposed. These cosmologies are based on reinterpretation of the matter–energy stress tensor in Einstein's equations. This modifies the usual adiabatic energy conservation laws, thereby including irreversible matter creation. This creation corresponds to an irreversible energy flow from the gravitational field to the created matter constituents. This point of view results from consideration of the thermodynamics of open systems in the framework of cosmology. It is shown that the second law of thermodynamics requires that space–time transforms into matter, while the inverse transformation is forbidden. It appears that the usual initial singularity associated with the big bang is structurally unstable with respect to irreversible matter creation. The corresponding cosmological history therefore starts from an instability of the vacuum rather than from a singularity. This is exemplified in the framework of a simple phenomenological model that leads to a three-stage cosmology: the first drives the cosmological system from the initial instability to a de Sitter regime, and the last connects with the usual matter–radiation Robertson–Walker universe. Matter as well as entropy creation occurs during the first two stages, while the third involves the traditional cosmological evolution. A remarkable fact is that the de Sitter stage appears to be an attractor independent of the initial fluctuation. This is also the case for all the physical predictions involving the present Robertson–Walker universe. Most results obtained previously, in the framework of quantum field theory, can now be obtained on a macroscopic basis. It is shown that this description leads quite naturally to the introduction of primeval black holes as the intermediate stage between the Minkowski vacuum and the present matter–radiation universe. The instability at the origin of the universe is the result of fluctuations of the vacuum in which black holes act as membranes that stabilize these fluctuations. In short, black holes will be produced by an "inverse" Hawking radiation process and, once formed, will decompose into "real" matter through the usual Hawking radiation. In this way, the irreversible transformation of space–time into matter can be described as a phase separation between matter and gravitation in which black holes play the role of "critical nuclei."**

Section I. Introduction

Very few physical theories are in such a paradoxical situation as cosmology. On the one hand, our universe is characterized by a considerable entropy content, mainly in the form of black body radiation. On the other hand, Einstein's equations are adiabatic and reversible, and consequently they cannot provide, by themselves, an explanation of the origin of cosmological entropy.

As is well known, matter may be produced quantum mechanically in the framework of Einstein's equations. The energy of these produced particles is then extracted from that of the (classical) gravitational field (1–4). But these semiclassical Einstein equations are adiabatic and reversible as well, and consequently they are unable to provide the entropy burst accompanying the production of matter. Moreover, the quantum nature of these equations renders the various results highly sensitive to quantum subtleties in curved space–times such as the inevitable subtraction procedures.

The aim of the present work is to overcome these problems and present a phenomenological model of the origin of the instability leading from the Minkowskian vacuum to the present universe. We propose a phenomenological macroscopic approach that allows for both particles and entropy production in the early universe. We shall indeed show that the thermodynamics of open systems (5, 6‡), as applied to cosmology, leads naturally to a reinterpretation, in Einstein's equations, of the matter stress–energy tensor (7, 8), which then takes into account matter creation on a macroscopic level. To do this, we extend the concept of adiabatic transformation from closed to open systems. This will then apply to systems in which matter–creation occurs.

These considerations lead to an extension of thermodynamics as associated with cosmology. Traditionally, in addition to the geometrical state of the universe, the two physical variables describing the cosmological fluid are the energy–density ρ and the pressure p. Einstein's equations are then solved assuming an equation of state $\rho = \rho(p)$. In our case, however, a supplementary variable, the particle density n, enters naturally into the description. This leads to an enlargement of traditional cosmology, which we shall develop in *Section 3*. An important conclusion is that, in these circumstances, creation of matter can occur only as an irreversible process, corresponding to an irreversible transfer of energy from the gravitational field to the created matter. More precisely, the transition from traditional cosmology (involving only adiabatic transformations for closed systems) to adiabatic transformations for open systems, leads to modification of the expression for energy conservation (*Section 2*). As a result, a supplementary effective pressure p_c, related to particle creation, appears. This pressure is always negative or zero, according to the second law.§

Moreover, it is shown that the big bang singularity, present in traditional cosmology, is structurally unstable with respect to irreversible matter creation. Such a cosmology starts from an instability (10–12) of the Minkowski vacuum and not from a singularity. We specify these properties in *Section 3*, in the framework of a simple phenomenological model of irreversible particle production. This model provides a cosmological history that evolves in three stages (*Section 4*): (*i*) A creation period that drives the cosmological system from an initial fluctuation of the vacuum to a de Sitter space; (*ii*) the de Sitter space exists during the decay

‡Recently, two of us (J.G. and I.P.) have considered the problem of a redefinition of matter–density and pressure in the stress tensor. To some extent, the work reported here continues this attempt.

§It should be emphasized that our approach differs from that used by Hoyle to take into account matter creation with a "C-field" (see, for example, ref. 9).

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time of its constituents; and (*iii*) a phase transition turns the de Sitter space into the usual Robertson–Walker universe, which extends to the present.

A fundamental fact is that the de Sitter regime appears as an attractor whose properties are independent of the initial fluctuation. This implies, in turn, that all the physical parameters characterizing the present Robertson–Walker stage are independent of this initial fluctuation. In particular, the specific entropy per baryon $S = n_\gamma/n_b$ depends only on two characteristic times of the theory: the creation period time τ_c and the de Sitter decay time τ_d, which are obtained in *Section 4*.

Our model takes the second law of thermodynamics into account from the beginning. Indeed, the energy transfer from space–time curvature to matter is treated as an irreversible process, leading to a burst of entropy associated with the creation of matter. Therefore, the distinction between space–time and matter is provided by entropy creation. The latter occurs only during the two first cosmological stages while, as is well known, the Robertson–Walker universe evolves adiabatically on the cosmological scale.

It is interesting that "mini black holes" seem to play an essential role in these fluctuations that lead from the Minkowski vacuum to the present universe. It is tempting to relate this to the fact that black holes play the role of membranes stabilizing the vacuum fluctuations. In this way, the primeval stage corresponding to the formation of the universe can be viewed as a phase separation between gravitation and matter. A few remarks concerning this mechanism are presented in *Section 5*.

Section 2. Thermodynamics of Matter Creation

Let us consider a volume V containing N particles. For a closed system, N is constant. The corresponding thermodynamic conservation of internal energy E is expressed by

$$dE = dQ - p\,dV, \qquad [2\text{-}1]$$

where dQ is the heat received by the system during time $d\tau$. We may rewrite relation **2-1** in the form

$$d(\rho/n) = dq - pd(1/n) \qquad [2\text{-}2]$$

with $\rho = E/V$, $n = N/V$, $dq = dQ/N$.

Relation **2-2** is also valid for open systems in which N is time dependent. In this case, relation **2-2** leads to a modification of Eq. **2-1** that explicitly takes into account the variation of the number of particles:

$$d(\rho V) = dQ - p\,dV + (h/n)d(nV), \text{ where } h = \rho + p \qquad [2\text{-}3]$$

is the enthalpy (per unit volume). For closed systems, adiabatic transformations ($dQ = 0$) are defined by the relation

$$d(\rho V) + p\,dV = 0. \qquad [2\text{-}4]$$

The extension to open systems is described by the equation

$$d(\rho V) + p\,dV - (h/n)d(nV) = 0. \qquad [2\text{-}5]$$

In such a transformation, the "heat" received by the system is entirely due to the change in the number of particles. In our cosmological perspective (see *Section 3*), this change is due to the transfer of energy from gravitation to matter. Hence, the creation of matter acts as a source of internal energy.

We turn now to the second law of thermodynamics. As usual, we decompose the entropy change into an entropy flow d_eS and an entropy creation d_iS:

$$dS = d_eS + d_iS \text{ with } d_iS \geq 0. \qquad [2\text{-}6]$$

To evaluate the entropy flow and the entropy production, we start from the total differential of the entropy

$$T\,d(sV) = d(\rho V) + p\,dV - \mu\,d(nV), \qquad [2\text{-}7]$$

where μ is the chemical potential

$$s = S/V \qquad \mu n = h - Ts \text{ with } \mu \geq 0,\ s \geq 0. \qquad [2\text{-}8]$$

For closed systems and adiabatic transformation, relation **2-7** leads to

$$dS = 0 \text{ and } d_iS = 0. \qquad [2\text{-}9]$$

Let us consider the effect of matter creation. We consider homogeneous systems and we therefore expect that we still have $d_eS = 0$. In contrast, matter creation contributes to the entropy production. We have therefore

$$T\,d_iS = T\,dS = (h/n)d(nV) - \mu\,d(nV) = T(s/n)d(nV) \geq 0. \qquad [2\text{-}10]$$

This inequality, in the cosmological context developed in *Section 3*, implies that space–time can produce matter, while the reverse process is thermodynamically forbidden.

The relation between space–time and matter ceases to be symmetrical, since particle production, occurring at the expense of gravitational energy, appears to be an irreversible process. A situation somewhat similar corresponds to systems in which macroscopic kinetic energy can be transformed into internal energy. This kinetic energy then appears as a source term in the entropy balance equation (5, 6). The microscopic interpretation of this process in which space–time is converted into matter will be discussed in *Section 5*.

Relation **2-7** can be written in a number of equivalent forms such as

$$\dot{\rho} = (h/n)\dot{n} \qquad [2\text{-}11]$$

$$p = (n\dot{\rho} - \rho\dot{n})/\dot{n}, \qquad [2\text{-}12]$$

where an overdot denotes the derivative with respect to time. It is interesting to note that the energy creation $\dot{\rho}$ and the particle creation $\dot{n}$ determine the pressure p. As examples, let us note that $\rho = mn$ implies $p = 0$ and, furthermore, $\rho = aT^4$, $n = bT^3$ implies $p = \rho/3$.

Section 3. Alternative Cosmologies

The traditional Einstein equations

$$G_{\mu\nu} = \kappa T_{\mu\nu}, \qquad [3\text{-}1]$$

as applied to isotropic and homogeneous universes, involve the macroscopic stress tensor $T_{\mu\nu}$, which corresponds to a perfect fluid. It is characterized by a phenomenological energy density ρ and pressure $\tilde{p}$ given by

$$\rho = T_0^0 \text{ and } \tilde{p}\delta_j^i = T_j^i. \qquad [3\text{-}2]$$

In addition to the Einstein equations (**3-1**) we use the Bianchi identities

$$G^{\mu}_{\nu;\mu} = 0,$$

which, for homogeneous and isotropic universes, lead to the well-known relation

$$d(\rho V) = -\tilde{p}\,dV, \qquad [3\text{-}3]$$

where V represents any comoving volume. In traditional cosmology, one identifies this equation with an adiabatic evolution for a closed system corresponding to Eq. **2-4**. This involves an identification between $\tilde{p}$ and the thermodynamical pressure p.

On the contrary, in the presence of matter creation, the appropriate analysis must be performed in the context of open systems. This involves the inclusion of a supplementary pressure p_c, as we may write Eq. **2-5** in a form similar to Eq. **2-4**, namely,

$$d(\rho V) = -(p + p_c)dV, \quad \textbf{[3-4]}$$

where

$$p_c = -\frac{h}{n}\frac{d(nV)}{dV} = -\frac{\rho + p}{n}\frac{d(nV)}{dV}. \quad \textbf{[3-5]}$$

Creation of matter corresponds to a supplementary pressure p_c, which must be considered as part of the cosmological pressure $\bar{p}$ entering into the Einstein equations

$$\bar{p} = p + p_c, \quad \textbf{[3-6]}$$

where p is the *true* thermodynamic pressure.

We shall now apply these general considerations concerning open systems to cosmology. In the case of an isotropic and homogeneous universe, we choose for V the value

$$V = R^3(\tau),$$

then

$$p_c = -\frac{\rho + p}{3nH}(\dot{n} + 3Hn), \quad \textbf{[3-7]}$$

where $R(\tau)$ is the Robertson–Walker function and $H = \dot{R}/R$ is the Hubble function.

Because of the thermodynamic inequality **2-10**, this extension of the Einstein equations to open systems now includes the second law of thermodynamics. This implies that, in the presence of matter creation, the usual cosmological Einstein equations become

$$\kappa\rho = 3H^2 + k/R^2 \quad \textbf{[3-8]}$$

$$\dot{\rho} = (\dot{n}/n)(\rho + p). \quad \textbf{[3-9]}$$

The corresponding cosmologies are more general, because they involve three functions—ρ, p, n—rather than ρ and p only. We have, for instance, a class of de Sitter spaces with $\dot{\rho} = \dot{n} = 0$, arbitrary pressure p, and $p_c = -h$.

Therefore our approach "rehabilitates" the de Sitter universe, which is now compatible with the existence of matter endowed with a usual equation of state. We may even consider classes of different de Sitter universes, such as "incoherent" de Sitter universes ($\rho = mn$, $n = cst$, $p = 0$) and "radiative" de Sitter spaces ($T = cst$, $n = bT^3$, $\rho = aT^4$).

It has been suggested that the expansion of the universe provides the arrow of time. A transition from an expanding universe into a contracting one would then invert the arrow of time. We do not confirm this idea, as inequality **2-10** implies only that

$$\dot{n} + 3Hn \geq 0, \quad \textbf{[3-10]}$$

which is compatible with $H \geq 0$, $H = 0$, and $H \leq 0$. However, in the case of a de Sitter universe, in which $\dot{n} = 0$ by virtue of Eq. **3-9**, relation **3-10** reduces to $H \geq 0$. Then only an *expanding de Sitter universe is thermodynamically possible.*

Section 4. Thermodynamic Properties of the Present Universe

Let us consider a homogeneous and isotropic universe with zero spatial curvature. The first Einstein equation (**3-9**) reduces to

$$\kappa\rho = 3H^2. \quad \textbf{[4-1]}$$

Moreover, we assume the simple relation $\rho = Mn$ between ρ and n. To complete the problem we need one more relation between n and $R(\tau)$. In accordance with the thermodynamic inequality **2-10**, the simplest possible relation between irreversible particle creation and the Hubble function H is

$$\frac{1}{R^3}\frac{d(nR^3)}{d\tau} = \alpha H^2 \geq 0 \text{ with } \alpha \geq 0. \quad \textbf{[4-2]}$$

For $\alpha = 0$ we recover the usual Robertson–Walker description with its typical big bang singularity. However, for $\alpha \neq 0$, using Eq. **3-9**, we obtain

$$p = 0,\ \rho = (3/\kappa)H^2$$

$$\frac{1}{nR^3}\frac{d(nR^3)}{d\tau} = \frac{\alpha\kappa M}{3} \geq 0. \quad \textbf{[4-3]}$$

This leads to

$$n(\tau)R^3(\tau) = n_0R_0^3e^{\alpha\kappa M\tau/3}$$

and

$$R(\tau) = (1 + C(e^{\alpha\kappa M\tau/6} - 1))^{2/3},$$

where

$$C = \frac{9}{\kappa M\alpha}\left(\frac{\kappa M n_0}{3}\right)^{1/2}.$$

The universe starts with $R_0 = 1$, at $\tau = 0$, with a particle density n_0 describing the initial fluctuation. It therefore follows that the presence of dissipative particle creation ($\alpha \neq 0$) leads to the disappearance of the big bang singularity. In other words, the singularity of the Einstein equations is *structurally unstable* with respect to irreversible particle creation. Hence, a cosmology that includes particle creation starts from an instability ($n_0 \neq 0$) and not from a singularity.

After a characteristic time

$$\tau_c = 6/\alpha\kappa M \quad \textbf{[4-4]}$$

the universe reaches a de Sitter regime.

The de Sitter era corresponds to

$$R_d(\tau) = C^{2/3}e^{\alpha\kappa M\tau/9} = C^{2/3}e^{2\tau/3\tau_c}$$

$$H_d = \alpha\kappa M/9 = 2/3\tau_c$$

$$n_d = (\kappa M/27)\alpha^2. \quad \textbf{[4-5]}$$

It is remarkable that all the de Sitter physical quantities such as H_d, n_d, ρ_d are independent of C. This cosmological state therefore appears to be an attractor independent of the initial fluctuation. No essential change would be introduced if instead of relation **4-2** we started with a more general kinetic equation involving an expansion in powers of H, starting with H^2.

We expect the zero spatial curvature to be the natural starting point, which is then taken over to the de Sitter universe as well as into the matter–radiation universe that follows.

The de Sitter stage survives during the decay time τ_d of its constituents and then connects continuously to a usual (adiabatic) matter–radiation Robertson–Walker universe.

Let us investigate the consequences of the transition between the two regimes. Although our considerations up to this point are quite general, the matching of the de Sitter universe to a Friedman–Lemaitre universe involves supplementary assumptions. We indeed expect the post-de Sitter universe to be of a great complexity, involving a variety of particles and evolving gradually to the present matter–radiation universe. To avoid the introduction of unknown parameters, we directly match the de Sitter universe to a matter–radiation universe. This matching is most easily performed in conformal coordinates, namely,

$$ds^2 = R^2(t)(dt^2 - dl^2) = d\tau^2 - R^2(\tau)dl^2, \quad \textbf{[4-6]}$$

where t is the conformal time coordinate.

In these coordinates the de Sitter Robertson–Walker function becomes

$$R_d(\tau) = C^{2/3}e^{H_d\tau} \equiv R_d(t) = C^{2/3}/(1 - C^{2/3}H_d t). \quad [4\text{-}7]$$

The present adiabatic matter–radiation regime is characterized by the matter energy density ρ_b and the radiation energy density ρ_γ, related to the Robertson–Walker function by

$$\kappa\rho_b = 3a/R^3,\ \kappa\rho_\gamma = 3b/R^4, \text{ and } \rho_\gamma = (\pi^2/15)T^4, \quad [4\text{-}8]$$

where a and b are constants related to the total number N_b of baryons and photons N_γ in a volume R^3 and T is the black-body radiation temperature.

$$N_b = n_b R^3 = \frac{3a}{\kappa m_b},\ N_\gamma = n_\gamma R^3 = \frac{2\zeta(3)}{\pi^2}\left(\frac{45}{\pi^2}\right)^{3/4}\left(\frac{b}{\kappa}\right)^{3/4}, \quad [4\text{-}9]$$

where m_b is chosen to be the proton mass (4.75×10^{15} m^{-1}) (the system of units used here is such that $h = c = k_B = 1$ corresponding to a Planck mass $M_p = 1.234 \times 10^{34}$ m^{-1}).

The solution of the Einstein equation **4-1** (for $a \neq 0$) leads directly to

$$R(t) = (a/4)t^2 - (b/a).$$

The continuous connection (up to the first derivative, involving a discontinuity in the pressure p) at the decay time τ_d (or in conformal time t_d) then gives

$$C^{2/3}(1 - C^{2/3}H_d t_d)^{-1} = (a/4)t_d^2 - (b/a)$$

$$H_d C^{4/3}(1 - C^{2/3}H_d t_d)^{-2} = (a/2)t_d$$

$$1 - C^{2/3}H_d t_d = e^{-H_d\tau_d}. \quad [4\text{-}10]$$

This enables us to determine a and b (when $e^{H_d\tau_d} >> 1$)

$$a \simeq 2H_d^2 C^2 e^{2H_d\tau_d}\ b \simeq H_d^2 C^{8/3} e^{4H_d\tau_d}. \quad [4\text{-}11]$$

This implies that the (constant) specific entropy $S_{\gamma b}$ per baryon is

$$S_{\gamma b} = \frac{n_\gamma}{n_b} = \frac{\zeta(3)}{3\pi^2}\left(\frac{45}{\pi^2}\right)^{3/4}\kappa^{1/4} m_b H_d^{-1/2} e^{H_d\tau_d}. \quad [4\text{-}12]$$

Hence the specific entropy per baryon is entirely fixed by the knowledge of the two characteristic times τ_c and τ_d (see relation **4-5**). Rather than $S_{\gamma b}$, which involves the baryon mass m_b explicitly, it is interesting to deduce from relations **4-8** and **4-11** the value of the adiabatic invariant $\rho_\gamma/T\rho_b$:

$$\frac{\rho_\gamma}{T\rho_b} = \frac{b^{3/4}}{a}\left(\frac{\pi^2\kappa}{45}\right)^{1/4}. \quad [4\text{-}13]$$

Similarly, as shown below, the black body radiation temperature of the present universe can be obtained in terms of these characteristic times.

At this point, it is tempting to consider the "proto-particles" of mass M as black holes as suggested earlier (13) on the basis of quantum mechanical considerations. In the framework of the present model, the unusual feature of the black hole model is that both H_d and τ_d can be expressed in terms of a single parameter, namely, the mass M of the produced particles. The value of H_d is (14)

$$H_d^2 = (\pi^2/45)(\kappa^3 M^4)^{-1}, \quad [4\text{-}14]$$

which corresponds to

$$H_d = (\pi^2/45)^{1/2}(M_p^3/M^2). \quad [4\text{-}15]$$

As these particles are interpreted as mini black holes (13, 14), their decay time is consequently identified with their evaporation time (15). For $N = 2$ helicity states (photons) and one type of massive scalar particle, one has:

$$\tau_d = (640/81\pi)\kappa^2 M^3 = (640/81\pi)\cdot(M^3/M_p^4)$$
$$\simeq 2.5\,(M/M_p)^3\tau_p, \quad [4\text{-}16]$$

where $\tau_p = 2.7 \times 10^{-43}$ sec is the Planck time. The explicit values for α, τ_c, and $S_{\gamma b}$ follow then from relations **4-5** and **4-12**. These are

$$\tau_c = 2/3H_d = (20/\pi^2)^{1/2}(M^2/M_p^3) \simeq 1.42\,(M/M_p)^2\tau_p$$

$$\alpha = 9H_d/\kappa M = 9(\pi^2/45)^{1/2}(M_p^5/M^3)$$

and finally

$$S_{\gamma b} = 7.31 \times 10^{-20}(M/M_p)e^{1.1778M/M_p}.$$

More generally, when one takes into account the N helicity states associated with the massless particles present in the cosmological medium as well as one type of massive scalar particle, the value of $S_{\gamma b}$ is expressed as

$$S_{\gamma b} = 7.31 \times 10^{-20}(2/N)(M/M_p)$$
$$\times \exp[1.1778(M/M_p)3\sqrt{N}/\sqrt{2}(N+1)].$$

The value of $S_{\gamma b}$ is of course very sensitive to the value of the mass M.

$N = 2$	$N = 100$
$M/M_p = 40 \rightarrow S_{\gamma b} = 8.46 \times 10^2$	$M/M_p = 200 \rightarrow S_{\gamma b} = 8.97 \times 10^2$
$M/M_p = 50 \rightarrow S_{\gamma b} = 1.38 \times 10^8$	$M/M_p = 250 \rightarrow S_{\gamma b} = 2.64 \times 10^8$
$M/M_p = 60 \rightarrow S_{\gamma b} = 2.16 \times 10^{13}$	$M/M_p = 300 \rightarrow S_{\gamma b} = 7.45 \times 10^{13}$

With $N = 2$, the correct observed value for the specific entropy $S_{\gamma b}$ is obtained with values of the mass very close to the quantum mechanically predicted mass ($53.3\,M_p$) (16). In contrast, for $N = 100$ similar values for $S_{\gamma b}$ are obtained with a mass increased roughly by a factor $\simeq 5$.

The present value of the black body radiation temperature can be obtained in our model if we specify the present value of the Hubble function H_p. Indeed, one can deduce H_p from the expression for the present adiabatic Robertson–Walker function $R(t)$:

$$H_p = \frac{a}{2}t_p\left(\frac{a}{4}t_p^2 - \frac{b}{a}\right)^{-2}. \quad [4\text{-}17]$$

In the present matter-dominated cosmological stage, where $\rho_b \simeq 3H_p^2/\kappa$, we have

$$(a/4)t_p^2 >> b/a$$

This implies that

$$H_p \simeq 8(at_p^3)^{-1} \qquad R_p \simeq (aH_p^{-2})^{1/3}. \quad [4\text{-}18]$$

It results from relation **4-8** for the radiation energy density ρ_γ that

$$T_p = \left(\frac{45}{\pi^2}\kappa^{-1}\right)^{1/4}\frac{b^{1/4}}{a^{1/3}}H_p^{2/3} \quad [4\text{-}19]$$

$$T_p(K) \simeq 2.82 \times 10^{-9}$$
$$\times \left(\frac{H_p}{75\ \text{km}\cdot\text{s}^{-1}\cdot\text{Mpc}^{-1}}\right)^{2/3}\left(\frac{M}{M_p}\right)^{1/3} e^{0.3926M/M_p}. \quad [4\text{-}20]$$

The present value of H_p is bounded by 50 km·s^{-1}·Mpc $\leq H_p \leq$ 100 km·s^{-1}·Mpc (Mpc, million parsec; 1 parsec = 3.09 ×

10^{16} m). The observed black body temperature is 2.7 K.

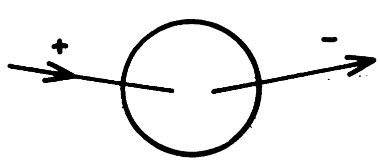
For any N we have the following relation between the black body temperature and the specific entropy:

$$T_p = 6.74 \times 10^{-3} S_{\gamma b}^{1/3} \left(\frac{H_p}{75\ \mathrm{km \cdot s^{-1} \cdot Mpc}}\right)^{2/3} \mathrm{K}. \qquad [4\text{-}21]$$

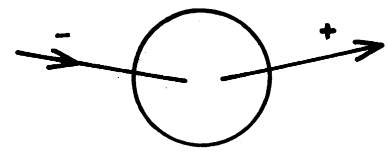
This delivers for $H_p = 75$ and $S_{\gamma b} = 10^8$, for example, the value $T_p = 3.13$ K.

Section 5. The Cosmological Instability: A Phase Separation Between Matter and Gravitation

To understand the observed large-scale structure of the world, we need not only some unification program for the forces involved but also a mechanism for the existence of the irreversible processes prevalent at all levels of physical description. We believe that this irreversibility comes from the dissymetrical relation between space–time and matter. In this view, creation of matter introduces a broken time symmetry into the Einstein equations. It is interesting that dissipation eliminates the need for an initial singularity, which is here replaced by the instability of the Minkowski background. This instability results (10–12) from fluctuations of the geometrical Minkowskian background associated to quantum mechanical fluctuations of matter fields. This leads to the appearance of unstable massive particles of mass $m << M$, creating a background of negative energy. If a sufficient number of such masses appear in the same adequate volume element, this would give rise to the formation of a black hole. We expect that these black holes act as membranes that stabilize such fluctuations. In other words, the formation of black holes would correspond to the absorption of positive energy (mass) and emission of negative energy (gravitation). Because of the universal coupling between matter and gravitation, it is easy to conceive mechanisms in which fluctuating masses $m << M$ are agglomerated in mini black holes with mass M and are thereby prevented from returning to the vacuum. In short, we have the following schemes: First, primordial mini black holes are formed associated with the absorption of a positive energy flow and the emission of a negative one, as shown below.



Then, these black holes decay through the usual Hawking mechanism: absorption of a negative energy flow and emission of a positive one, as shown below.



In essence, we have here a model of initial instability as a phase separation between matter and gravitation. This is in agreement with the quantum mechanical description of the vacuum in terms of two interacting lagrangians as presented previously (1–4). These considerations have been limited to an homogeneous and isotropic universe; they have not yet been extended to more general models.

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